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Green Roof Growing Substrates: Types, Ingredients, Composition and Properties[1]

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Abstract

Although development of low (extensive) and high (intensive) maintenance green roof systems has progressed significantly, studies on the function of the growing substrate as a living constituent are lacking. The objective of this review paper is to summarize current scientific knowledge on the components, composition, and characteristics of green roof substrates and to identify future research needs. Due to variations in climate and desired plant types, there is no universal growing substrate. An appropriate substrate is expected to provide permanent physical support for plants and possess a fine balance between free drainage and adequate plant available water and nutrient retention. Typical substrate components include minerals in natural or modified forms such as sand, lava rock, or expanded shale, clay and slate; recycled waste materials like crushed bricks or tiles, crushed or aerated concrete and subsoil; stabilized organic matter such as composts; and plastic materials and slow release fertilizers. Proportions of components vary among substrates based on target vegetation, green roof type, and other considerations. Better green roof management for maximum benefits will require characterizing, quantifying and understanding the impacts of plant species and building attributes such as aspect, slope, height and heating on substrate performance, and should be considered for future research.

Index words: green roof, growing substrate, components, properties, research.

Significance to the Nursery Industry

This review paper presents a summary of current information on green roof substrates and identifies areas that need research consideration. As a result, it will serve as a useful quick reference for scientists, horticulturists, green roof experts and other interest groups. The information presented may also stimulate research that is currently lacking to support and improve the industry. Green roof substrate research is necessary because it is the key component of any green roof system. As such, a better understanding of its function and alteration under different conditions and time are valuable to managing green roofs for maximum ecological and economic benefits. The need for improved management efficiency is important because green roofs are increasingly becoming a popular component of the environmentally sustainable home and the urban environment. Solid evidence of the services provided by green roofs is key to their continued acceptance and growth of the industry.

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Introduction

Green roofs offer several ecological, economic and other benefits to the urban environment. These include mitigation of the urban heat island effect, provision of natural habitat for animals and plants, reduction of dust, smog and noise levels, improved storm water management and water quality, and reduced energy use. Green roofs also provide owner incentives such as increased life of roofs and enhanced quality of life (11). One of the key components of a green roof system that permits achievement of these beneficial functions is the growing substrate. Like natural soils, a green roof growing substrate provides physical support for plants and supplies essential plant nutrients. Unlike natural soils which develop in-situ over time, green roof substrates are manufactured soils that may contain a variety of natural, synthetic, and modified ingredients. The challenge with manufactured soils is to achieve a favorable balance between optimal physical properties (e.g., rapid drainage and low bulk density) and optimal plant growth properties (e.g., high cation exchange capacity and plant available nutrients). Despite the importance of these factors to the functionality of the green roof, information on the growing substrate is widely scattered and often embedded in small sections of technical manuals or review publications. Since green roofs are still a relatively new phenomenon in the United States, there is a need to examine the available information related specifically to the green roof growing substrate, including the ingredients commonly used and their associated physical and chemical properties. Even though there are review articles on the general benefits of green roofs (19, 30), there are no documents focused specifically on the growing substrate. A few authors have provided some guidelines for the selection of substrate components (16, 18) and others (3) have discussed their basic characteristics. Combining the information from these various sources into a single review article will provide handy information for researchers and private sector groups interested in further development or improvement of green roof substrate and their plant-sustaining properties. Therefore, the objective of this paper is to review and summarize scientific and commercial literature related to the components, composition and characteristics of current green roof substrates and identify future research needs.

Growth Substrate Types

There are generally two categories of green roof designs depending on the amount of maintenance they require. Intensive green roofs require a high level of maintenance because they are designed to function more like a conventional terrestrial garden where there are a variety of plants that require individual attention. In contrast, extensive green roofs require less maintenance because they are designed to have an ecological rather than aesthetic function. Plants on an extensive green roof require little specialized attention and people interact very little or not at all with the extensive green roof. In actuality, it is becoming increasingly common to find elements of both the intensive and extensive designs combined into a single roof top (11).

Although there are various degrees of green roof design ranging from intensive to extensive, the ingredients used in the green roof growing substrates do not vary greatly among green roof types. However the depth of growing substrate is varied, with deeper planting depths used on intensive green roofs and shallower depths on extensive roofs. Current green roof growing substrates generally fall into two broad categories namely, non-commercial and commercial. Non-commercial green roof substrates are usually non-proprietary blends manufactured by individuals or researchers using recommended materials and guidelines. However, commercial growing substrates come in forms ready for use with their composition shrouded in secrecy and patents (14). Examples include VegTech 'roof soil' (VegTech AB, Fagerås, Sweden), Sopraflor (Soprema Inc., Drummondville, QC, Canada), Hydrolite (Axter Ltd, Ipswich, Suffolk, UK) and Litetop Soil (American Hydrotech Inc., Chicago, IL). These growing substrate formulations may be green roof- or vegetation-type specific (11).

Growing Substrate Components

Green roof growing substrates are generally a blend of natural and artificial minerals, recycled or waste materials, and organic matter. Sometimes plastics are included to reduce substrate bulk density while complete slow release fertilizers may be added to substrates to provide nutrients and boost vegetation establishment. Natural minerals used for green roof growing substrates include sand, clay, gravel, and lava (scoria) pumice (Table 1), while artificial or modified minerals employed include expanded shale, clay & slate (ESCS), perlite, vermiculite, and rockwool (Table 2) (4, 11, 13, 27, 33, 36). Recycled materials used for manufacturing green roof growing substrates include crushed clay bricks or tiles, crushed roof tiles, crushed or aerated concrete, and subsoil (Table 3) (4, 8, 11, 14). Using recycled materials may reduce transportation needs during green roof construction, but most importantly it turns locally generated low-value materials into a useful raw material (14). Synthetic plastic type materials are also used in some green roof growing substrates, including encapsulated styrofoams and urea-formaldehyde resin foams (Table 3) (22, 23, 31). Sources of organic matter in growing roof substrates include peat, compost, coconut coir, and decomposed sawdust or bark (Table 4) (10, 11, 18).

Most green roof growing substrates also require incorporated fertilization to establish or sustain plant growth. Nutricote Type 100 and 180 (Chisso-Asahi Fertilizer Co., Ltd., , Tokyo, Japan) with varying analyses and Multicote 8 M extra (18N-6P-12K; Haifa Chemicals, Haifa Bay, Israel) are examples of slow release fertilizers added to green roof substrates (13, 14, 27, 33). Foliar fertilizers like Nutrileaf 60 (Miller, Hanover, PA, USA) and conventional fertilizers like Complesal (6.3N-5.2P-14.1K-1.2Mg-8S; AgrEvo Hellas S.A., Athens, Greece) have also been used to promote plant growth in green roof systems (31). The advantages and disadvantages of the various green roof substrate components are summarized in Tables 1 through 4. While blends of these traditional ingredients appear to be performing satisfactorily as substrate, it is necessary to expand the ingredient horizon by examining other materials for their suitability for green roof substrate formulation. Good candidates will consist of

Table 1. Advantages and disadvantages of natural mineral components used in green roof growing substrates.

Material	Advantages	Disadvantages
Sand	• Provides sturdy anchorage for plants and facilitates wetting of the medium (7, 21) • Causes no pH effects if free of carbonates and other contaminants (7)	• May create saturation problems or may not hold enough moisture depending on grade (11) • Heavy • Negligible source of nutrients • Holds nutrients poorly
Clay	• Good moisture retention (7) • High cation exchange capacity and nutrients retention (7)	• Gradual loss from medium may clog drainage layers and fabrics (26)
Lava (scoria)	• Lightweight and porous (11)	• High pH may require adjustment with dolomite (21)
Pumice	• Lightweight and porous (11)	• Expensive (21)
Gravel	• Stable and provides strong support for plants • May enhance good drainage	• Heavy compared to other minerals (11, 24) • Poor water retention (26) • Provides no nutrients

Table 2. Advantages and disadvantages of artificial or modified mineral components used in green roof growing substrates.

Material	Advantages	Disadvantages
Perlite	• Porous and sterile (21) • Stable, improves drainage and does not disintegrate in a mix (7)	• Coarser particles are crushable during transportation (21) • Has no cation exchange capacity (CEC), contains no plant nutrients and holds water poorly (7) • Contain small quantities of fluoride that may cause toxicity in some plants (7)
Vermiculite	• Light weight and porous but its porosity is lower than that of perlite in mixes (7) • Relatively high CEC and retains water better than perlite (7) • Supplies magnesium and potassium (21) • Immobilizes ammonium and phosphate (7)	• Deteriorates over time (7, 21) • Absorbs anions poorly except PO_4^{3-} (7) • Generally holds water poorly
Expanded shale, clay and slate (ESCS)	• Porous and lightweight and provides good moisture retention (11) • Have high CEC hence good nutrient retention and supply (15) • Do not break down or decay (15) • Inert, sterile and non toxic therefore have no pathogen, weed and disease problems and stable under environmental conditions (15)	• Too light to provide good anchorage for plants when used alone (11) • Tend to have alkaline pH and that may affect the availability of micronutrients (e.g. boron and iron)
Rockwool	• Light weight, porous and regulates air and water supply (7, 11, 21)	• Does not contain or hold nutrients (7, 11)

lightweight and porous materials that have the capacity to retain and slowly release both cations and anions. Since high fertility may be disadvantageous to roof plants in terms of establishment characteristics and stress tolerance, the presence of a nutrient moderator in green roof substrate may buffer nutrient availability in the root zone, enhance plant stress tolerance and encourage healthy plant growth.

Composition of Growing Substrate

The composition of a substrate may vary depending on green roof type, target vegetation, climatic conditions, and other factors such as availability and expense of components. However, there are certain ingredients that are commonly used in most green roof growing substrates. The ideal green roof substrate must be stable, permanent, and lightweight and it must aerate, drain, and hold nutrients well (18). It is recommended that the bulk of the substrate be mineral based. On a volume basis, the mineral composition may vary from 80–100% with organic matter and small amounts of a starter or complete slow release fertilizer containing both macro- and micro-nutrients making up the remaining 0–20% (3). Expanded shale, clay, and slate (ESCS) materials are commonly used in green roof substrates because they are lightweight and porous, giving them the ability to retain a quantity of plant available water within their internal pores while also allowing excess water to drain freely from the large intra-aggregate pores (35). Research (33) has shown that 10 cm deep sub-

Table 3. Advantages and disadvantages of recycled or waste and plastic foam materials useful for green roof growing substrates.

Material	Advantages	Disadvantages
Crushed clay bricks, tiles or brick rubble	• Stable and strong material (11) • Can hold some moisture (11)	• Possible high pH problems due to presence of mortar and cement (11)
Crushed concrete	• Cheap and readily available at demolition sites (11)	• Alkaline and has little moisture holding capacity (11)
Aerated concrete	• Capacity to absorb and hold water high when mixed with organic matter (8)	• May require periodic maintenance (8) • Not applicable to all roof types (8)
Subsoil	• Readily available at construction sites as a by-product (11)	• Heavy and poor in plant nutrients (11)
Styrofoam	• Does not breakdown or compress in use (7) • Improves aeration and drainage (21)	• Insignificant cation exchange capacity (21) • Contains and holds no nutrients (7) • Too light and exhibits electrostatic characteristics during mixing (7)
Urea-formaldehy resin foam	• Relatively high water absorption capacity	• Light and degrades slowly over time • Low pH and largely devoid of nutrients (7)
Styrofoam	• Improves aeration and drainage (21)	• Light, contains no nutrients and has insignificant cation exchange capacity (21)

Table 4. Advantages and disadvantages of organic materials used in green roof growing substrate formulations.

Material	Advantages	Disadvantages
Peat	• High cation exchange capacity (CEC) (7) • Low bulk density (21) • High water holding capacity and readily available water (21)	• Partially decomposed; additional decomposition will cause shrinkage of medium (21) • Poorly aerated when wet (21) • Stringy consistency depending on source (21) • Acidic and expensive (21) • May not rewet easily once very dry
Coir fiber dust	• Does not repel water (21) • Better water holding characteristics than most peats (21) • High potassium content (21)	• High amounts of chloride; low in calcium and sulfur • Liming material cannot be used to supply calcium because pH is close to 6 (21)
Composts (bark, poultry litter and yard waste)	• Provide high CEC and nutrients (21) • Enhance water holding capacity and readily available water (21) • High microbial counts and recycling value (18)	• High and variable salinity (21) • Potential ammonium toxicity with poultry litter compost (21) • Residual herbicide effects may occur depending on the source of the compost feed stock (18) • Weeds may occur in medium if the composting process is poor (18)
Worm castings	• High levels of essential trace minerals (21) • Supply phosphorus and potassium (21) • Structurally better than ordinary compost (21)	• Zinc toxicity possible if medium pH drops below 5 (21)

strates comprising as much as 80% heat-expanded slate and small amounts of slow release fertilizer (50 $g \cdot m^{-2} \cdot yr^{-1}$) could adequately support succulents like stonecrop (*Sedum* spp.). Deeper substrates may require higher amounts of fertilizer but the key is to apply just enough quantities to sustain plant growth and minimize nutrient discharge in runoff. ESCS materials have the ability to absorb up to 0.9 $g \cdot kg^{-1}$ inorganic phosphorus (P) (9, 17) and also the capacity to release the absorbed P to plants (39).

Unlike ESCS materials, sand is used in much smaller quantities for green roof substrates formulation. Recommended levels on percentage mass basis is 30% for extensive substrates and at most 50% for intensive substrates. Coarse sand with maximum diameter of 2 mm is usually preferred and should be safe if it meets the U.S. Golf Association (USGA) root zone specifications for putting greens (18). Despite its favorable drainage properties, gravel is not commonly used in green roof substrate formulations, probably due to its relatively heavy weight. The high weight of gravel is regarded as a disadvantage for roof applications (25). Also, it has poor moisture retention characteristics (26). Another disadvantage with sand and gravel materials is that they have no cation exchange capacity, so they do not contribute to the ability of the green roof substrate to retain essential plant nutrients.

Organic matter is usually added to substrates in the composted form because compost has high nutrient content, microbial count, and a recycling value (18). However, yard waste composts are preferred to manure compost because they tend to have lower levels of soluble salts (18). High levels of salt in substrate may lead to high electrical conductivity (EC) and may suppress plant establishment and growth. Regardless of the source, the addition of high amounts of organic matter to green roof substrates is not advisable because, besides having the potential to increase the saturated weight of the substrate (18), organic matter decomposition may result in substrate volume shrinkage (3, 11) and increased nutrient loss in roof runoff (29).

Inclusion of high levels of organic matter in green roof growing substrates may also create weed problems due to enhanced water and nutrient availability (14). Furthermore, fine material from the degradation of organic matter may filter down to the separation fabric and undergo further decomposition, which may form a slime that can inhibit drainage, affect plant growth, and increase the structural load (18). Increasing the level of fertility in the green roof growing substrate by adding high amounts of organic matter or fertilizer can promote the growth of lush foliage that may be more susceptible to abiotic environmental stresses, including heat and drought (11, 19) and biotic stresses such as insects, mites and diseases (32). Conversely, it was found that the survival rates of smooth aster (*Aster laevis* L.), junegrass (*Koeleria macrantha* Regel) and showy goldenrod (*Solidago speciosa* L.) were greater without fertilization (33) suggesting that better drought tolerance is associated with less plant biomass production. Similarly, a low to medium substrate fertility may promote chances for developing a more diverse plant community that may minimize the occurrence of dominant aggressive species (11). It must be noted that only stabilized or mature compost should be blended into a green roof growing substrate because unfinished or unstable compost could deprive the substrate of nitrogen and oxygen and may ultimately be harmful to plant growth (11, 18).

The right amount of organic material to add to a substrate is still a matter of debate, partly due to the influence of differing local climates. Organic matter decomposition will proceed relatively fast in warm humid climates, but at a slower rate in arid and cooler climates. The stability of the organic matter source will also affect how quickly it will decompose in a green roof setting. Freshly cured compost will decompose at a greater rate than a more humified, aged material (37). Therefore, the question of what type and how much organic matter to use in a green roof substrate requires regional research to generate specific appropriate answers. However, based on the current level of knowledge, green roof experts advise that substrates should be composed of no greater than 10–20% organic matter in humid climates (18). As examples, published compositions and properties of selected experimental extensive green roof substrates are provided in Table 5.

Physical Properties

Physical characteristics of concern for green roof substrates include bulk density, air filled and total porosity, available water holding capacity, capillary water rise, field capacity, perched water table, permanent wilting point and water release and desorption characteristics (3, 8, 16, 26). In a study involving a three year old green roof substrate, greater values were measured for porosity, free airspace (macropores), organic matter content and water holding capacity at the end of the experiment than at the beginning (20). This demonstrates that that the physical properties of green roof substrates are not constant and potential problems may arise over time.

The German *Guidelines for Planning, Execution, and Upkeep of Green-Roof Sites* (16) lists a suitable dry bulk density range of 600 to 1200 kg·m^{-3} for both extensive and intensive system growing substrates or 1000 to 1800 kg·m^{-3} at maximum plant available water content (i.e., 24 h after a saturated substrate is allowed to drain freely). At a bulk density of 1000 kg·m^{-3}, a 1-cm depth of growing substrate would weigh 10 kg·m^{-2}. Since most buildings are built to withstand weight loads of 100 to 120 kg·m^{-2}, the maximum

Table 5. Composition and properties of some experimental extensive-green roof growing substrates.

Author(s)	Medium components and composition(s)	Manufacturer[z]	Properties
13	40% HES[y] (3–5 mm particle size); 40% USGA grade sand; 10% Michigan peat; 5% dolomite; 3.33% composted yard waste and 1.67% composted turkey litter. Slow release fertilizer, Nutricote Type 100 (18N-6P-9K) was applied twice after planting at 100 g·m^{-2}.	Carolina Stalite Company, Salisbury, NC; Osburn Industries, Taylor, MI; Renewed Earth, Kalamazoo, MI; Herbruck's Saranac, MI Chisso-Asahi Fertilzer Co., Ltd, Tokyo, Japan	*At planting* EC, 3.29 mmho·cm^{-1}; pH 7.9
33	(1) 60% HES (7.9–9.5 mm particle size), 25% USGA grade sand, 10% peat and 5% compost[x]; (2) 70% HES, 18.75% sand, 7.5% peat and 3.75% compost; (3) 80% HES, 12.5% sand; 5% peat and 2.5% compost; (4) 90% HES, 6.25% sand, 2.5% peat, 1.25% compost; (5) 100% HES and 0% for sand, peat and compost Slow release fertilizer, Nutricote Type 180 (13N-5.7P-10.8K) was added to each substrate at 100 g·m^{-2} at planting and 331 g·m^{-2} after study initiation	Carolina Stalite Company, Salisbury, NC; Osburn Industries, Taylor, MI; Herbruck's Poultry Ranch, Saranac, MI and Charter Township of Ypsilanti, Ypsilanti, MI Chisso-Asahi Fertilzer Co., Ltd, Tokyo, Japan	*For the 60% HES substrate* bulk density, 77–130 kg·m^{-3}; capillary pore space, 19.9%; non-capillary pore space, 21.4%; infiltration rate, 51.6 cm·h^{-1}; water holding capacity at 0.01 MPA, 17.1%
36	40% HES (3–5 mm particle size); 40% USGA grade sand; 10% Michigan peat; 5% dolomite; 3.33% composted yard waste and 1.67% composted turkey litter Slow release fertilizer, Nutricote Type 100 (20N-7P_2O_5-10K_2O), was added to each substrate at planting at 100 g·m^{-2}	Carolina Stalite Company, Salisbury, NC; Osburn Industries, Taylor, MI; Renewed Earth, Kalamazoo, MI; Herbruck's Saranac, MI Chisso-Asahi Fertilzer Co., Ltd, Tokyo, Japan	*At 0.01MPa* bulk density, 130 kg·m^{-3}; capillary pore space, 19.9%; noncapillary pore space, 21.4%; infiltration rate, 51.6 cm·h^{-1}; water holding capacity, 17.1%; saturated weight 150 kg·m^{-3} *At planting* EC, 0.33 S·m^{-1}; pH 7.9
27	60% HES (7.9–9.5 mm particle size); 25% USGA grade sand; 5% aged compost and 10% Michigan peat *Fertilizer at Planting* Nutricote Type 180 (13-13-13) at 100 g·m^{-2} *Supplemental Fertilizer* Applied 12-12-12 at 30 g·m^{-2} 66 days after planting	Carolina Stalite Company, Salisbury, NC; Osburn Industries, Taylor, MI; Herbruck's Poultry Ranch, Saranac, MI and Charter Township of Ypsilanti, Ypsilanti, MI Chisso-Asahi Fertilzer Co., Ltd, Tokyo, Japan Chisso-Asahi Fertilizer Co., Ltd, Tokyo, Japan	*At 0.1 MPa* Bulk density, 1.3 g·cm^{-3}; capillary pore space, 19.9%; noncapillary pore space, 21.4%; infiltration rate, 51.6 cm·h^{-1}; water holding capacity, 17.1%; saturated weight, 1.5 g·cm^{-3}
24	Not specified – described as 'Mixed ruderal soil'	N/A	pH 7.8; plant available water, 11.6 liters·m^{-2}; field capacity soil moisture content, 18%; organic C, 2.1%; %N 0.1%; Pb, 108.8 mg·kg^{-1}; Cd, 0.1 mg·kg^{-1}

[z]Manufacturers follow the same order of listing as the components

[y]Heat expanded slate

[x]2:1 volume mix of aged poultry manure (Herbruck's Poultry Ranch, Saranac, MI) and composted yard waste (Charter Township of Ypsilanti, Ypsilanti, MI).

depth of a 1000 kg·m^{-3} growth substrate would be 10 to 12 cm and heavier substrates would decrease the maximum possible depth even more.

Growing substrates for an extensive green roof system should have a maximum plant available water capacity of at least 35% (v/v) with a concurrent air content of at least 10% (16). Corresponding values for the substrate of an intensive green roof system should be ≥ 45% and ≥ 15%, respectively (18). Some researchers (3) contended that the ideal volume composition of a green roof substrate for good plant growth in terms of solids, water, and air should be 40, 40, and 20%, respectively. Others (18) have concluded that acceptable water permeability for an extensive green roof growth substrate should be > 0.36 cm·hr^{-1} while that for an intensive system should be > 3.6 cm·hr^{-1}. However, those guidelines were based on European research (16) where rainfall characteristics are different from the severe convective storms typical of the Midwest, the Southern Great Plains regions and Southeastern United States.

Chemical and Biological Properties

The chemical and biological properties of a green roof substrate are vital for its optimum function. Important chemical properties include pH, buffering capacity, cation exchange capacity (CEC) and chemical stability. Biological activity is centered on organic matter decomposition in the substrate, recycling of biomass and roots from established vegetation and the absence of disease pathogens and other destructive soil organisms (3, 16).

Like the other properties, substrate pH may vary but it must be within the range that allows nutrient uptake by green roof plants and should be stable for long term plant health (3, 18). This implies that local environmental challenges like acid rains should be factored into substrate formulation to ensure roof plant growth. With pH range of 7.0 to 9.0, ESCS is good for buffering so their presence in substrates may be useful in areas prone to acid rainfall events. It was found that the pH of acidic rainwater was moderated close to neutral when it percolated through an expanded clay green roof substrate (3). At the same time, this high pH of ESCS could limit the availability of some micronutrients because plant nutrients are usually most available between pH 5.5 and 7.0. Alternatively, acidity and alkalinity may be corrected with lime dust and sulfur applications, respectively (18). It is therefore likely that, the rather high pH of some of the experimental substrates provided in Table 5 were due to the presence of dolomite and/or heat expanded slate.

The major sources of cation exchange capacity (CEC) in green roof growing substrates are organic matter and clays. However, some green roof growing substrates may have little or no CEC depending on their formulation. Also, because of their light weight, the traditional methods for measuring and describing CEC may not apply to green roof substrates (3).

The paucity of essential plant nutrients in the green roof substrates, especially N, P, K, Mg, and several trace elements, may limit fertility and necessitate that synthetic fertilizer be blended with the substrate (16, 18). However, pre-blending fertilizer into growing substrates may have environmental disadvantages if plants are not established immediately after the growing substrate is installed on the roof. Fertilizer nutrients that are not utilized by plants may leach from the substrate and end up in the storm water drainage system (18). Long term efficient management of these various properties under different vegetation cover, stress and climatic conditions requires research that is currently lacking. Research is needed to better understand how specific organic and inorganic ingredients in the green roof substrate impact the retention, cycling and chemical forms of individual nutrients (e.g., NO_3-N versus NH_4-N). It may be possible to improve the green roof substrate by identifying and including ingredients that improve nutrient retention characteristics.

Depth of Growing Substrates

The depth of a growing substrate varies with the type of vegetation it is intended to support, which is usually dependent on the green roof type (i.e. extensive or intensive). It is generally believed that, the thinner the substrate depth, the shorter the list of plants that may thrive in it (38). Substrate depth is also linked to moisture retention (20, 28, 36). Substrate depths for extensive green roofs may vary from 2 to 15 cm (31) while those for intensive green roofs should be at least 15 cm (21) but may range up to 125 cm (24, 31). The semi-extensive growing substrate is a little deeper than the extensive substrate layer and ranges from 10 to 20 cm (11, 12). The actual upper limit of green roof substrate depth will be determined by the bulk density of the substrate and the maximum safe load bearing capacity of the roof. Some authors (11) have pointed out that substrate depth greater than 10 cm begin to cause structural damage due to loadings exceeding 120 kg·m^{-2}, which is a typical maximum safe load for most buildings.

Due to the harsh and extreme climatic conditions on the roof top, thinly laid green roof substrates require hardier plants which have minimal irrigation and fertilizer needs (3, 12). In contrast, the deeper substrates of intensive systems require more maintenance in terms of fertilization and supplementary irrigation to sustain the wider range of plant species for which they were designed (31). Studies have shown that plants survived better on 5.0 and 7.5 cm substrate layers compared to a 2.5 cm layer (13) suggesting that even for extensive green roofs, deeper substrates favor better plant establishment and survival. However, a minimum depth of 7 cm is recommended for extensive roofs in the United Kingdom because roof loads greater than 120 kg·m^{-3} (i.e. substrates thicker than 10 cm) can cause structural defects (11). On the other hand, it is suggested that green roof substrates in northern latitudes should be at least 10 cm (4 in) deep to minimize the effects of temperature fluctuations on water, nutrient and transport mechanisms necessary for plant survival (6). An alternative to green roof substrates is to use commercial pre-grown vegetation mats. However, these require fertilizer inputs and are susceptible to drought and therefore not recommended (11). On sloped roofs, extensive green roof substrates 4 cm deep and at 2% slope provided the greatest water retention (36). Similarly, studies conducted to examine the effects of 2, 7, 15, and 25% slopes on storm water retention on extensive roof platforms with same substrate depths (6 cm) revealed that the greatest retention of 85.6% was attained on platforms at 2% slope (20). Research is also needed to describe the effects of other building attributes on substrate changes and function.

Future Research Needs

Green roof substrates are essentially engineered ecosystems because they comprise living and non-living components suggesting that interaction between the two components could produce changes in the system overtime. Yet most green roof studies have focused on plant establishment and not the substrate. A few studies have examined the impacts of substrate depth on plant establishment and freezing injury (6, 27), storm runoff retention (20, 36), and nutrient release and weight reduction (31, 33) but studies pertaining to long term physical, biological, chemical substrate changes are lacking. Though most of these substrates contain stable mineral materials as their main components, biomass recycling promoted by established plants, water regime changes following weather extremes like cold and hot temperatures and very wet and dry cycles overtime could impact chemical, biological and possibly physical properties of the substrates and therefore need investigation. Knowing how different substrates change over time under similar and/or different conditions would enhance sustainable green roof management.

Some studies have shown that a slate-based growing substrate has better pH buffering capacity than a clay-based substrate in an extensive roof system (5). In addition, differences were observed in the recovery ability of the two substrates with additions of the same amounts of acid at different time intervals (5). Based on these observations, the researchers concluded that despite the apparent high pH buffering capacities of the substrates, their respective abilities to neutralize acid precipitation would diminish at different rates over time. As the substrate pH becomes more acidic, there is an increasing possibility of nutrient deficiencies and/or toxicities. The long-term acid-neutralization capability of green roofs in areas prone to acid rain and the impacts of pH shifts on microorganisms, nutrient cycles, and root health and distribution remain unanswered and therefore need further research.

Lantana (*Lantana camara*, L) caused pH increases in four green roof substrates in which they were grown (31) supporting the assertion that green roof plants may either reduce or raise substrate pH (5). This research observation indicates that pH buffering potential is not dependent on substrate components alone. As a result, more research is needed to quantify the short and long term effects of both pH reducing and raising plants on substrates to better manage green roof substrate under special purposes like acid rain containment.

Research at TU Berlin in Berlin-Charlottenburg revealed that 94.7% of Pb, 87.6% of Cd, 80.2% of NO_3^- and 67.5% of PO_4^{3-} applied to green roof plots were retained (25). Phosphate (PO_4^{3-}) retention was also observed to increase steadily over time due to plant establishment. Similarly, it was found that > 99% of Cd, Cu, Pb, and Zn were retained in a structural growing substrate composed of 50% expanded shale and 50% quartz sand (34). Addition of sphagnum peat moss to the growing substrate did not affect heavy metal leaching, but did increase the amount of fertilizer P lost through leaching. While these are significant observations, more research is needed to understand the ion exchange properties of green roof substrates and to identify how careful selection of ingredients can affect those properties.

Understanding the sorption and desorption characteristics of the substrates would help manage them to effectively function as sinks for potential surface and ground water pollutants. These kinds of research may encourage scientists to explore and test new materials for use in green roof substrates or lead to the improvement of currently utilized materials. Modified zeolites, for example, have the ability to retain both cations and anions and could be incorporated into green roof substrates in small quantities to improve retention of nutrients (PO_4^{3-} and NO_3^-) and other metal ions and minimize their loss in storm runoff. Research has shown that the addition of iron-oxide coated clinoptilolite zeolite to a sand root zone mix at 5% (w/w) significantly reduced PO_4^{3-} and NO_3^- leaching while supporting good turfgrass growth (1). Similarly, it has been reported that a surfactant-modified zeolite had high PO_4^{3-} retention and under continuous percolation supplied phosphorus slowly for 45 days (2). It has also been found that inclusion of 10 to 20% (v/v) natural clinoptilolite zeolite in an expanded shale based growing substrate increased the removal of Cd and Pb from contaminated runoff (32). It was also observed in a study that substrates containing resin foam measured significantly higher values for electrical conductivity at the end of the study compared to other substrates without because they retained much more water (31). Therefore incorporating materials that can retain and release anions and cations slowly into green roof substrates may also help reduce salt accumulation in substrates with high water retention and promote the establishment and growth of green roof plants.

Orientation and aspect are important variables in green roof systems just as they are in natural landscapes. Studies conducted on green roof platforms at 2% slope showed observable trends in substrate moisture content and temperature (27). Volumetric moisture content was greatest in the lower end of the platform slope whereas substrate temperatures were greatest at the higher end. This experimental observation has several implications for actual green roofs: (1) the concentration of moving water at lower green roof portions could concentrate nutrients, salts and metal ions creating a gradient across the roof slope and increase loss potential in runoff; (2) the resultant waterlogging and probably high electrical conductivity from solute accumulation could inhibit root and shoot growth; (3) higher root freezing injury in the winter is possible, especially for thin substrates; and (4) a combination of all these factors could lead to a change in substrate chemistry and affect the composition and numbers of both micro- and macro-organisms in the affected portions. While this may not be an issue for smaller flat roofs or very steep roofs, it could potentially affect plant survival in large green roofs with long gentle slopes. Like slope, aspect also affects substrate temperature and moisture regimes. It was observed that at the same slope, green roof substrates facing the south experienced much more fluctuations in temperature and moisture than those facing the north in a study conducted at the Technical University at Berlin, Germany (24). More research therefore needs to be conducted to assess the interaction between the green roof function and its physical orientation on the roof top at different latitudes and climates.

In the future, it is likely that most cities, especially in countries with limited land area, will expand vertically rather than horizontally. Given this reality, scientists and engineers must increase research efforts to identify possible future problems and solutions as green roofs progressively become an integral part of the urban environment. Other variables such as building height, shading, and winter heating, can possibly influence the performance of the green roof substrate and vegetation and therefore need to be quantified properly in replicated studies. An integrated research approach involving scientists from different disciplines is needed to acquiring a better understanding of the physical, chemical, and biological functions of green roof substrates and how green roof systems can impact local ecosystems. Green roof research presents a unique platform for collaborative research involving soil scientists, horticulturists and, biological and ecosystem engineers.

Just as soil is the most important part of a crop production system, the growing substrate is the most important part of any green roof system, be it intensive, extensive, or a combination of the two. The growing substrate impacts the types of plants that can be grown on the roof top and it supports and sustains these plants throughout the life of the green roof. The components, composition and thickness of a green roof substrate may vary according to green roof type, climatic conditions and geographical location, cost, availability of materials, suitability, and preference. Hence, there is no single universal green roof substrate. The ideal green roof growing substrate for any particular locale will vary and is therefore one that can provide stable anchorage for plants, including a favorable rooting environment, essential plant nutrients, and balance free drainage with plant available water for target plants. Ideally, the cost of manufacturing green roof substrates will be moderated by using locally available ingredients. While standards for developing green roof growing substrates exist in Germany and other parts of Europe, elsewhere, including the United States, they are either nonexistent or in their developmental stages. As such, it is logical to use German guidelines as a starting point and make modifications where necessary to suit local environmental conditions and availability of substrate components. Additional research is needed in the United States to identify appropriate growing substrates for major climatic regions. There is also the need to direct more research attention to the biological function of the substrate because its behavior has implications for services provided by green roof systems.

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